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Carnegie Mellon University

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ABSTRACT

This report describes a system for rapid tool manufacturing based on the integration of stereolithography and thermal spraying. With stereolithography apparatus (SLA), plastic prototype models are built directly from a vat of liquid photocurable polymer by selectively solidifying it with a scanning laser beam. Thermal spraying is then used to incrementally deposit metal onto the SLA models. A freestanding metal structure is formed by separating the metal shell from the plastic substrate. By mounting the shell in a frame and backing it up with appropriate materials, a broad range of tooling can be fabricated including injection molds, forming dies, and EDM electrodes. The system integrates SLA and thermal spraying into a CAD/CAM environment which includes design evaluation tools, robotic spray capability, and computer-aided process planning. Information flows efficiently from design through fabrication by incorporating a common geometric modeling system for part and process representations. Our goal is to demonstrate that automating and integrating these processes, within a unified modeling environment, can significantly improve productivity through greater design flexibility, rapid fabrication, and cost-reduction. We have established the system framework and developed several of the system components. This report describes a case-study for the application of this technology to injection mold manufacture.

1. Introduction

The capability to manufacture a wide variety of quality products in a timely and cost-effective response to market requirements is the key to global competitiveness. The opportunities for improving manufacturing technology range across the entire spectrum of industries, materials, and manufacturing techniques. There is no single technological innovation which by itself will significantly improve productivity; rather it is a systems issue which involves rethinking many manufacturing activities. One such activity is the manufacture of tooling (i.e. design, prototype, and fabrication) such as dies and molds required for the high-volume production methods that generate most of our manufactured products. Tooling manufacture is typically an expensive and time-consuming process. The reasons lie not only in the fabrication costs and time constraints imposed by conventional machining methods, but also in the organizational framework. In most organizations, different groups employ different processes to design and manufacture tools and products. And the expertise in tool design and product design reside in different groups, impeding communications between them. The representational and physical models used in design, prototyping, and manufacturing, are often incompatible with one another, so transitions between the stages are time-consuming and error-prone. Products often make several complete cycles through design, prototyping, and fabrication before reaching mass production. Thus, new product development or product modification implies a long series of iterative changes for both product manufactures and toolmakers. For all these reasons, a rapid and smooth transition from product concept to mass-production remains a challenge.

This report describes the development of a unified CAD/CAM tool manufacturing system to address this challenge for an injection molding paradigm. In this system, both prototype and tooling fabrication are based upon compatible shaping deposition processes, while the underlying geometric and process models share a common representational scheme. Our goal is to demonstrate that automating and integrating these processes can significantly improve productivity through greater design flexibility, rapid fabrication, and cost-reduction.

Shaping deposition processes build three-dimensional shapes by incremental material build-up of thin layers, and can make geometrically complex parts with little difficulty. These processes include, selective laser sintering [4], laminated object manufacturing [1], ballistic powder metallurgy [11], three dimensional printing [17], stereolithography, and near-net thermal spraying. Our system incorporates the commercially available technologies: stereolithography apparatus (SLA) and arc spray equipment. Stereolithography[1] is a new process which creates plastic models directly from a vat of liquid photocurable polymer by selectively solidifying it with a scanning laser beam. As the laser beam draws on the liquid surface it creates cross-sections of the solid shape. Complete three dimensional shapes are built up by drawing cross-sections on top of each other with each new layer, in turn, being lowered into the vat by an elevator mechanism. It is the first commercialized system that constructs physical objects by simple scanning and would be infeasible without a CAD front end; for practicality, the parts must be designed on the computer. Stereolithography is excellent for rapidly producing plastic prototype models.

In arc spraying, metal wire is melted in an electric arc, atomized, and sprayed onto a substrate surface. On contact, the sprayed material solidifies and forms a surface coating. Typical uses include applying wear and heat resistant coatings, and worn part restoration. While such applications are wide-spread, the use of thermal spraying to construct three-dimensional near net shapes has received considerably less attention. For this application, spray coatings are repeatedly applied to incrementally deposit multiple fused layers which, when separated from the substrate, form a free-standing shell with the shape of the substrate surface. By mounting the shell in a frame and backing it up with appropriate materials, a broad range of tooling can be fabricated including injection molds, forming dies, and EDM electrodes. For example, the cavities of injection molds can be fabricated by direct deposition of metal onto plastic SLA

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[1]Stereolithography has been commercialized by 3D Systems, Inc. (Valencia, California)

2. Stereolithography

Quickly creating prototype parts is useful for visualization, model building, design verification, and marketing evaluation. Highly skilled model builders rely on conventional machining, NC machining, and clay for prototyping, and must work closely with part designers to assure proper interpretation of the design drawings, sketches, or computer renderings. The process is costly and time-consuming, particularly for complex geometries

Stereolithography is one process which attempts to solve these problems by quickly making plastic prototypes of arbitrary geometric complexity directly from the computer models of the parts. The stereolithography apparatus (SLA) does not require experienced model makers and the machine runs unattended once the building operation is started. It is relatively straight forward for the designer to program and run the SLA himself.

SLA is the product of 3D Systems, Inc. of Valencia, California. Their system, which is depicted in Figure 2-1, is composed of a vat of photosensitive liquid polymer, an x-y scanning ultraviolet laser beam with a 0.010 inch beam diameter, a z-axis elevator in the vat, and a process control computer. The laser light is focused on the liquid's surface and cures the polymer making solid forms wherever the focused light has scanned. The depth of cure is dosage dependent and is a function of the laser power and scanning speed. The process control computer is coupled to a user supplied CAD solid modeling system. The vat dimensions are 9 inches in length, width, and height (20 inch vats are in development). The physical object to be created, as described by a boundary representation model[2], is first 'sliced' into thin cross-sectional layers along the z-axis. For each slice, the laser's trajectory is dictated by the cross-sections boundary and by the bounded region .

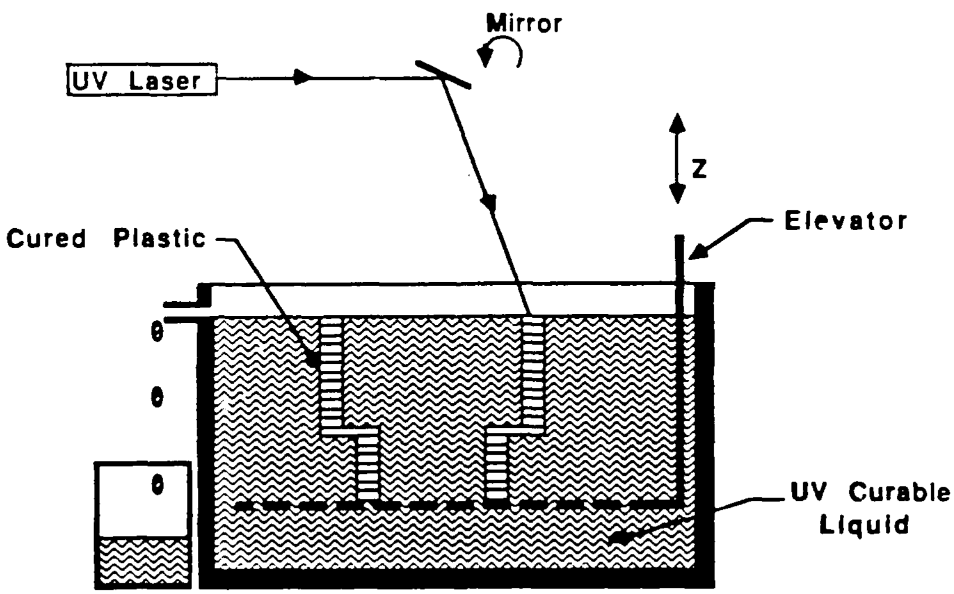

Figure 2-1: Stereolithography Apparatus

The elevator platform is initially positioned at the surface of the liquid. As the laser draws a cross-section

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[2]In the 3D Systems device, this is a triangulated, planar surface PHIGS B-Rep.

ir x-y plane, a solid layer is formed on the elevator platform. After the first slice has been scanned, the platform is lowered in preparation for the next layer. The layer thicknesses typically vary between 0.005 to 0.020 inches. The next layer is then drawn in the same way and adheres to the previous layer. As succeeding layers are formed, a three-dimensional plastic object builds-up in the vat, growing from bottom to top.

To wet the newly solidified layer with fresh liquid in preparation for making the next layer, the elevator is lowered well below the liquid surface allowing the liquid to flow over formed layer. The elevator is then raised to the next layer's scanning position. The polymers are fairly viscous (imagine warm honey), so some time is required to permit the liquid surface of the vat to again become flat. This dipping process takes some time, called the 'dip-delay'. The dip-delay becomes quite long for very thin slice thicknesses since it takes longer for a thin layer of liquid to level out than for a thick layer. It also becomes longer as the surface area increases.

To save time, the SLA laser does not fully cure each cross section. Rather the laser cures the boundary of a section, and then cures an internal structure, or honeycomb, that traps the uncured fluid. Top and bottom surfaces, on the other hand, are fully cured. These surfaces are cured by commanding the laser to draw the whole surface with overlapping lines; the result of this operation is called skin-fill. This operation is applied to layers that are horizontal and layers that are *nearly* horizontal. Final curing under separate ultra-violet lights solidifies the complete part.

Planning the SLA process consists of several interrelated decisions. Trade-offs between these decisions can directly affect the speed of making a part, including postprocessing time, the part's dimensional accuracy, and the surface quality of the part. Briefly, the primary decisions include:

- *Support Structure Design:* Part designs must incorporate support structures, such as trusses, buttresses, and piers, to support cross-sections during construction and to support the entire structure until it is fully cured. For example in Figure 2-2, when the first layer of the ledge is drawn it is thin and fragile and may break off or warp without additional support. A truss is therefore provided to support the ledge. Also, in the figure, when the first layer of the overhang is drawn, it is not connected to the rest of the part body and would float away without the additional pier support.

  The support structures are broken off and sanded down after the model is fully cured. It is desirable to use minimal support structure to minimize the amount of manual postprocesing required, as well as minimize the time required to draw the structures.

- *Part Orientation:* The orientation of the part in the vat affects all aspects of the SLA process performance, particularly surface quality, build time, and support structure complexity. Sloped surfaces in the SLA process inherently have a stepped surface texture due to the 2-1/2 dimensional layered build-up. This effect can be minimized by orienting surfaces to give them steep slopes or, best, by placing them in a horizontal orientation. While reducing the stepped surface, though, this may detract from other performance aspects. For example, a long, narrow, cylinder will build quickly if it is built on its side. This yields a highly stepped surface, though. Re-orienting the part with its major axis in the z direction will eliminate the stepped surface, but with the side effect of greatly increasing build time because of the greater number of layers. The support structure, however, is simplified to merely supporting the bottom, in contrast to supporting a whole side. The designer/SLA programmer must weigh these process decisions against one another in order to meet an overall goal of, say, minimum build time, best surface quality, or minimum support structure.

- *Slice Thicknesses:* The slice thickness may be varied within a part, thinner sections contributing to better appearance of the sloped surfaces. However, thinner sections increase the build times by requiring more layers and longer dip-delays. Another trade-off comes into play here, too. Thicker layers make a stronger part while it is in the vat, but require slower laser speeds to permit curing to deeper depths.

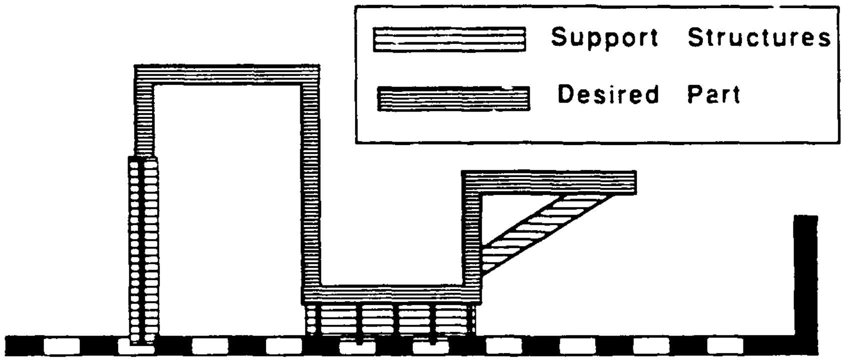


Figure 2-2: Support Structures

Many of these planning problems as well as other current SLA limitations can be minimized with improvements in SLA hardware and resins. With on going development by 3D Systems, and other new commercial ventures, there will be improvements in laser speed and accuracy, the resolution in layer thickness, support-structure requirements, dip-delays, and the allowable part sizes. Our goal is to enhance the SLA process by addressing the CAD/CAM integration issue by:

1. Creating efficient slicing and vector generation algorithms which operate directly within the unifying geometric modeller "NOODLES", and

2. Using the NOODLES structures, incorporate computer-aided process planners to help the designer make the process decisions to achieve the desired performance.

The algorithm for directly slicing design models and generating drawing vectors within the NOODLES structure is described in this report. The SLA planning system has not yet been developed. However, several software tools within NOODLES are described which will facilitate process planning and design evaluation including feature extraction and verification of geometric modifications.

3. Sprayed Tooling

Tooling can be fabricated with arc spraying using appropriate substrate patterns Examples which demonstrate this process for fabricating injection molds using SLA patterns are described below and compared with conventional pattern making techniques. The combination of stereolithography with thermal spraying provides a tooling fabrication process which builds directly upon prototype models. These models are rapidly produced and the ability to modify them for spraying applications is straightforward.

The concept of sprayed metal tooling has been in existence for decades [8] and was initially based upon flame spray technology. Flame spraying was relatively unsuccessful because the excessive heat transferred to substrate patterns could easily distort the model surface [18]. More recently, electric arc spraying has been used successfully in commercial applications due to its superior thermal efficiency and minimized heat transfer to the substrate. The arc spray process, in Figure 3-1, uses two spools of metal wire which are fed to a spray gun where the wire tips form consumable electrodes. A high current is passed through the electrodes creating an arc which melts the wire tips. The molten particles are atomized by a high pressure air jet, directed at the tips, and are accelerated to high velocities in the air stream. These particles strike the substrate surface where they flatten out and immediately solidify. In this application, the sprayed material adheres to the substrate by mechanical bonding and forms a surface coating. Additional layers are deposited on the thin surface coatings and form a thick metal shell where interparticle bonding is primarily metalurgical [9]. By using low melting point metals, such as zinc alloys, the total thermal energy of the particles as they impinge upon the substrate surface is relatively low. Therefore SLA plastic substrates are not distorted by this process. The cooling air stream also helps to prevent distortion of the plastic substrate.

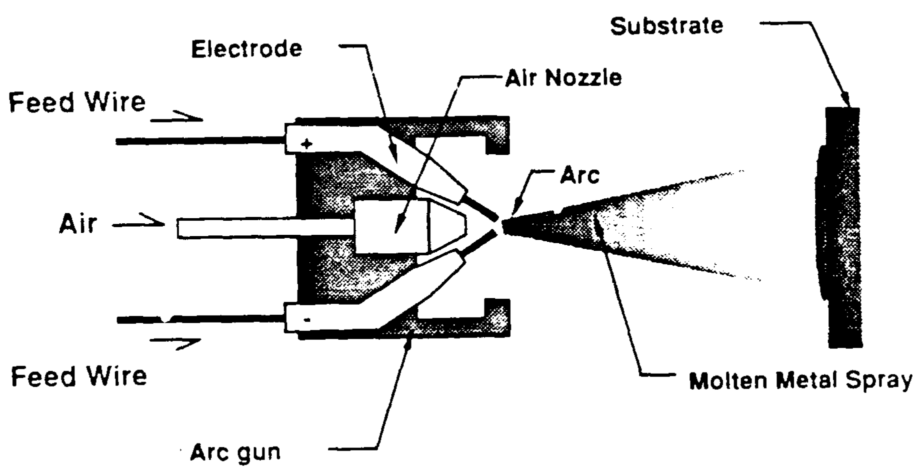


Figure 3-1: Electric Arc Spraying

Figure 3-2 represents a cross-sectional view of a conventional machined injection mold for molding the plastic piece also shown in the figure. The holes represent cooling/heating channels, and the injection geometry is that of a simple sprue gate. Alternatively, the fabrication steps for building a sprayed mold using SLA patterns are depicted in Figure 3-3. The steps are:

- **STEP 1:** Build SLA pattern used to make one mold half. This pattern is the compliment of the interior of this mold half. In this example, the mold pattern includes the partial part shape, a parting plane, and sprue gate.
- **STEP 2:** Apply a water soluble release agent onto the plastic pattern, such as polyvinyl alcohol (PVA), to facilitate separation of metal from plastic.

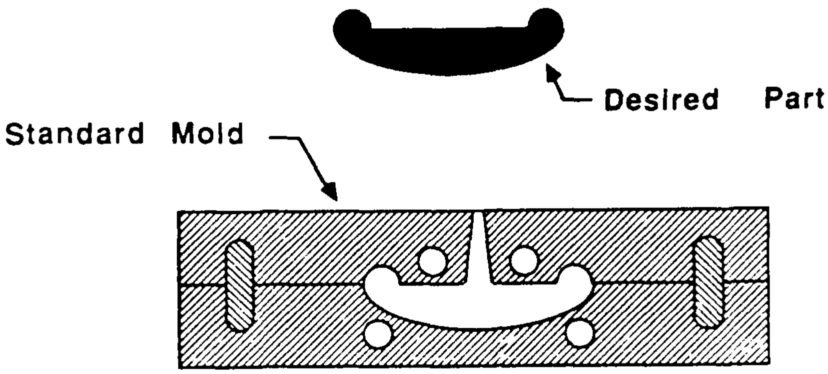


Figure 3-2: Conventional Mold

- **STEP 3:** Place a metal frame onto the pattern.
- **STEP 4:** Spray metal onto the pattern and around inside edge of frame. Alloyed zinc compositions are used for this particular process because of their relatively low residual stress. Sprayed shell thickness' are on the order of 1/16 to 1/4 inches. Fine pattern details are accurately replicated by this spray process.
- **STEP 5:** Lay in place copper tubing for heating and cooling channels for the injection mold process. Additional injection mold components, such as prefabricated ejector pin assemblies (not shown), can be added in STEP 1 and sprayed in place in STEP 4.
- **STEP 6:** Pour in a backing material to support the metal shell. Typical backing materials include epoxy with aluminum shot.
- **STEP 7:** Separate the substrate pattern from the mold half. This is facilitated by dissolving the PVA in water. This completes the fabrication of the first mold half.
- **STEP 8:** With SLA, build a model of the whole part to be molded, including runners and gates, and insert the model into the first mold half. This forms the pattern for spraying the second mold half.
- **STEP 9:** The second mold half is completed by repeating Steps 2 through 7.

The mold fabrication is completed by removing the SLA insert.

With these steps, we have fabricated the injection mold in Figure 3-4 for making a polyethelyne turbine blade. This example is interesting because of this shape's complexity and useful since molded plastic blades can be used for making castings for metal blades. This tool also includes a non-planar parting surface and a complex runner system. The fabrication of this tool requires three SLA mold patterns, shown in Figure 3-5, which can be built concurrently in the vat. The first pattern in Figure 3-5 is sprayed to make the first half of the mold. In contrast to the planar parting surface in the first example, the blade mold requires a non-planar parting surface to permit ejection of the molded blade from the tool. To create this pattern, the computer models of the blade and runner are embedded into the parting plane model in Figure 3-6 using simple union operators. A major advantage of using SLA to create spray patterns is demonstrated by this nonplanar parting plane example. Conventional methods of preparing spray patterns include partially embedding a complete prototype model of the part into melted paraffin or wax. When the paraffin, for example, cools it forms a planar parting surface around the remaining partial part shape. With this approach it is difficult to sculpt non-planar surfaces. Other approaches, which build up parting planes with sheet wax, clay, or plaster, are tedious and difficult. Machining complex patterns is time consuming and expensive. With SLA it is straight-forward to build complex patterns, along with the full prototype models, using computerized modeling. An additional advantage of SLA is that it is straight-forward to include the runner system in these models.

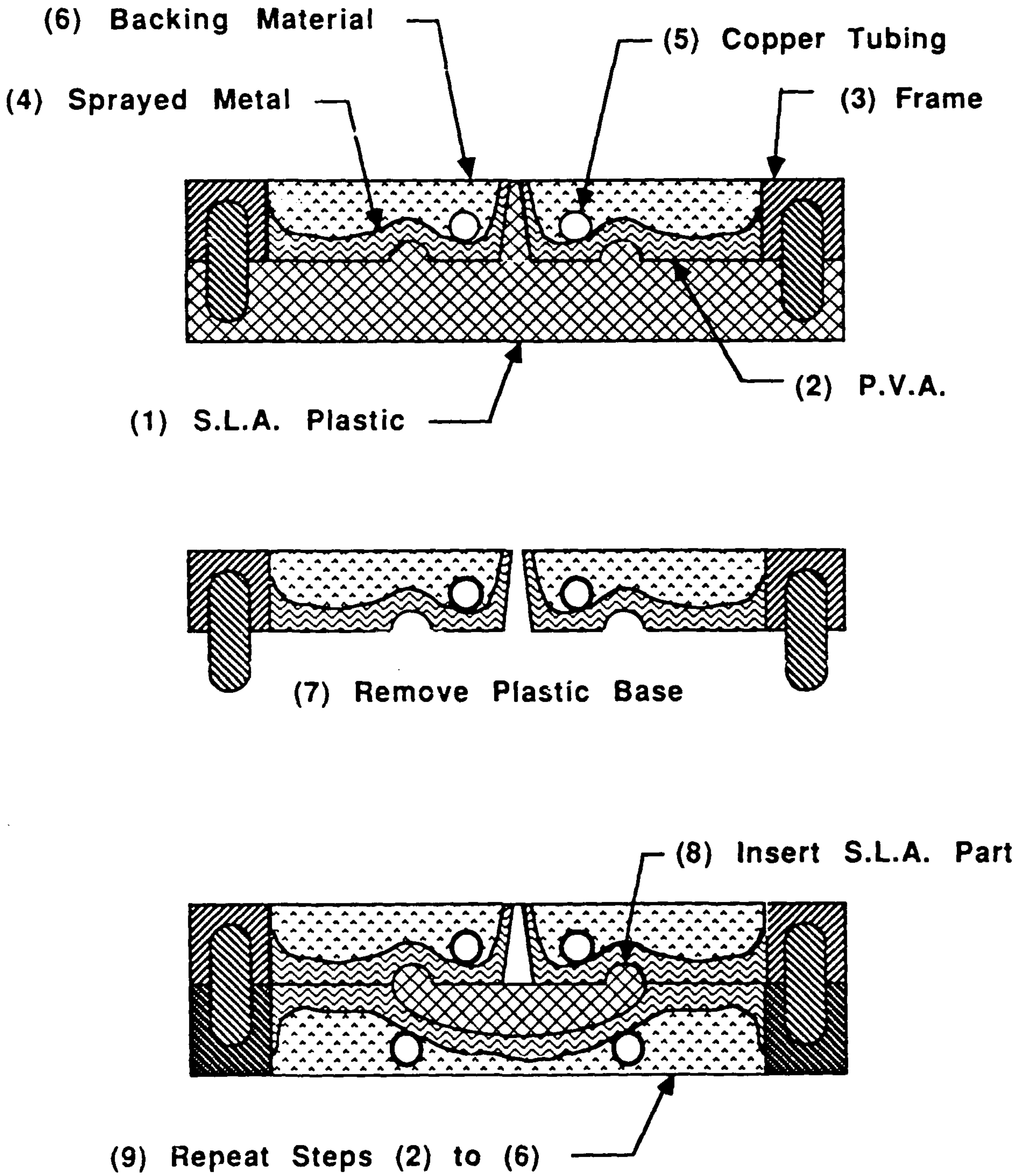


Figure 3-3: Sprayed Tool Process

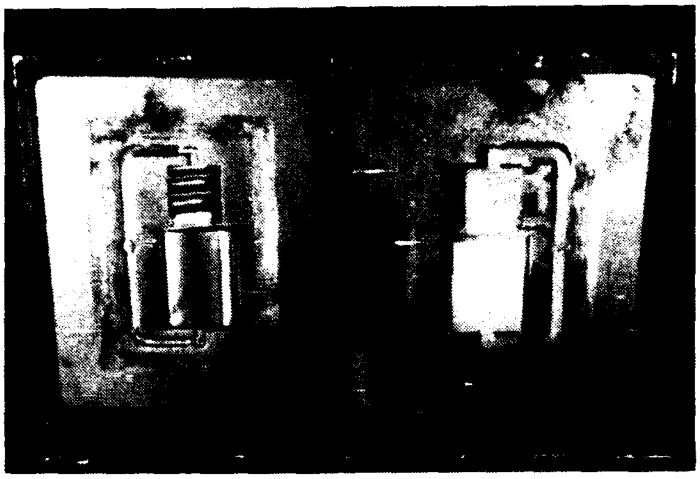


Figure 3-4: Sprayed Turbine Blade Mold

Once the first half of the mold is completed, the initial pattern is removed and SLA models of the blade with tab gates and the runner with the injection sprue gate are inserted into the mold cavities. The process is then repeated to build the second mold half.

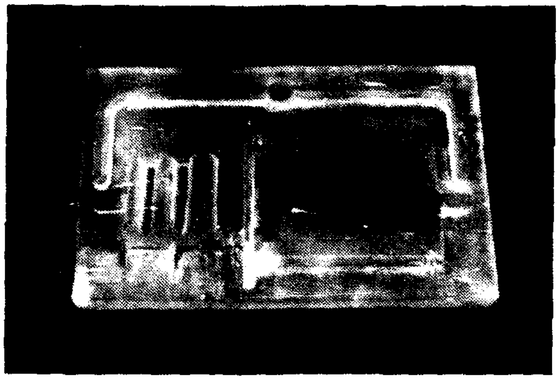
3.1 Limitations

It has been estimated [8, 14, 18] that there can be an order of magnitude reduction in the both the cost and time for producing injection mold tooling by thermal spraying in comparison with conventional machining methods. A reasonable assumption is that similar savings could also be realized for manufacturing other types of tooling such as forming dies or EDM electrodes. The question arises: Why hasn't the use of sprayed metal tooling proliferated considering these potential savings? There are several reasons:

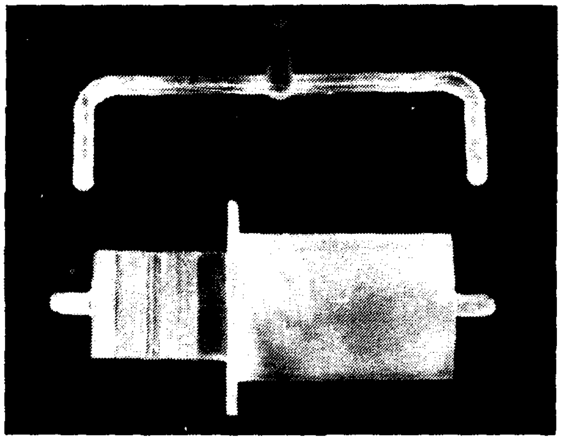
- **Zinc For Prototypes And Small Batch Applications:** Alloyed zinc is the only metal, as reported in literature, to be commercially successful in the fabrication of sprayed tooling using the aforementioned steps. More involved spray processes for steel deposition have been described [22], and there are reports that a handful of shops have built sprayed steel tools.

  During the spraying process, a temperature difference exists between the solid cooled layers and the freshly deposited hot layers. This thermal interface is subject to shear stress that becomes locked into the metal as residual stress. Because the net tensile forces are proportional to the deposit thickness, the maximum thickness that can be deposited is limited, since residual stress can lead to both separation of the metal from the substrate and to metal failure under load. The residual stress is in part correlated to the metal's melting point and Young's modulus. Useful thicknesses of zinc can be deposited because it has a relatively low melting point and Young's modulus. Also, with the low melting point zinc there is relatively little heat transfer to the substrate as the molten particles strike the substrate surface, thus minimizing distortion of the plastic surface. In contrast, the higher melting point and Young's modulus of appropriate steel compositions has limited their use for sprayed tooling.

  Zinc-based tools are relatively soft and are used primarily in prototyping and low-batch production applications. Their use in some low-stress applications, such as reaction injection molding, are possible on a higher-batch production basis. Prototype tooling is valuable for several reasons including making several hundred prototype parts for marketing and customer evaluation and for preliminary part testing. They are also useful for helping to



A. Pattern for first mold half



B. Inserts for second mold half

Figure 3-5: SLA Mold Patterns

evaluate tool design (e.g. to assess gate locations in the runner system) before committing to the more costly and long-lead time machined steel tool. Still, the sprayed tool process should be extended to fabricating steel tools with stronger backing materials if this technology is to play a more significant role in the manufacturing industry by providing production quality tooling.

- **Difficulty in Making Patterns:** The time and cost of making complex patterns with conventional machining is roughly the same as directly machining a tool. The benefits of sprayed tooling, including its speed and relatively low costs, are lost with conventional pattern making techniques. Improved pattern making abilities, such as provided for by shaping deposition fabrication, should be pursued.

- **Poor Process Control:** The sprayed tool process is currently limited to manual spraying by a skilled technician who must adjust process parameters such as arc voltage, wire feed rate, and air pressure, as well as control the gun motion relative to the substrate. Errors in the technician's judgment, operator fatigue, and poor spray technique yield poor quality tooling. The difficulties in quality control are accentuated when spraying large shapes which may take days to spray. Further, a systematic study of spray parameters in relation to the structural quality of sprayed metal shells for tooling applications has not been reported in the literature. Therefore methods and strategies to achieve consistent and predictable process

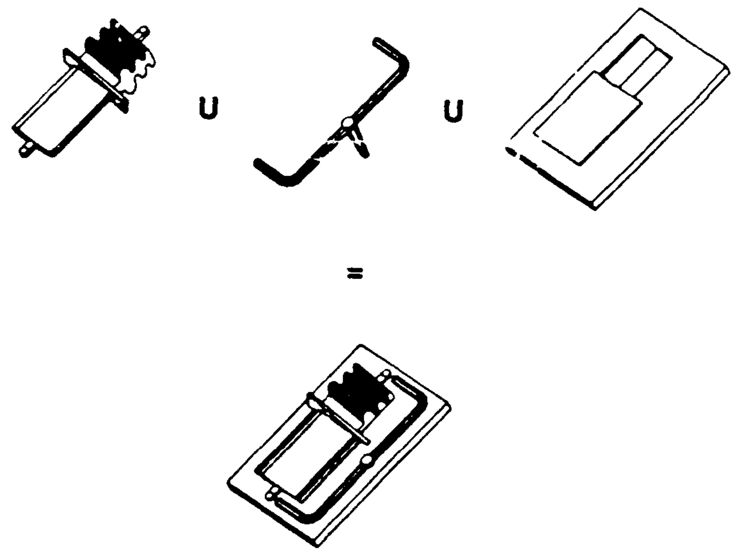


Figure 3-6: Parting Plane Model

performance must be developed.

- **Hard To Spray Certain Shapes:** The spray gun should ideally be aimed such that the trajectories of the atomized metal particles are close to the substrate's surface normals. This assures maximal splattering of the molten particles. There are part designs with geometric features which makes it difficult to spray these parts and satisfy this condition. Particles which strike the surface tangentially (e.g. approximately greater than 45 degrees from the normal) do not sufficiently splatter which results in either poor adhesion, increased porousity, or overspray. For example spraying concave surfaces with small aspect ratios (e.g. holes with small diameter-to-depth ratios) is difficult, if not impossible, since particles tend to strike the steep side walls at acute angles and bounce off into the hole. Therefore alternative strategies and technologies should be investigated to extend the scope of geometries which can be effectively sprayed.

There are several areas of research which should be investigated to address these issues. We have identified and demonstrated the use of SLA for rapidly fabricating the complex mold patterns. Another element is to incorporate robotic spraying, driven by an off-line path planner, which uses expert knowledge. The use of robotic automation has several ramifications. It will facilitate process control by its consistent and tireless performance and it can be easily integrated with sensory feedback (e.g. temperature measurement) for additional on-line control. We believe that the ability to reliably spray steel will require such tight process control. Complex shapes need tightly controlled spray trajectories. Robotic spraying will facilitate these trajectories. Off-line trajectory planning based on design models will not require tedious teach-by showing operations, and the incorporation of expert rules to formulate spray strategies has the potential to achieve optimal spray performance. This report presents a framework for the robotic spray planning system.

3.1.1 Integration

An issue of general concern for manufacturing is that tooling fabrication processes are not closely coupled to the design and prototyping stages of the manufacturing sequence. We are developing a system for manufacturing sprayed tooling which addresses these concerns by closely coupling prototyping and fabrication and linking them to the part design process. In this report, several of the system components have already been identified. These include a tool fabrication process that combines stereolithography with thermal spraying; the stereolithography parts are prototype parts, while the same computer models are easily modified to become mold or die patterns which are sprayed to make tooling. Another system component is the use of robotic spraying with spray paths planned directly from design models and using knowledge of the spray process requirements. Robotic spraying is presented in Chapter 5.

In conventional sprayed tool manufacture, the knowledge of and planning for the process has rested solely in the arc spray job-shop. Once the spray technician receives the tool order, he may identify design features which makes spraying difficult. For example, he may ask the part designer to add fillets, break corners, or change aspect ratios to assure proper deposited metal quality. Similar concerns have been identified for the molding process itself. These design iterations are time-consuming and costly. To reduce the number of iterations, parts should be designed for manufacturability by providing feedback to the designer about the ramifications of part geometry on the spraying and molding processes. Some of the modeling aspects of this issue are discussed below.

We feel the key to successful integration is to provide a modeling environment in which design, description of prototype models, and manufacturing methods are uniformly treated. In the next chapter this uniform modeling environment is discussed.

4. NOODLES MODELING

The representational requirements for modeling systems, including the levels of abstraction, the nature of the analyses, and the geometric manipulations, varies with the context of the model's use. In CAD/CAM applications, the models for design, analysis and evaluation, and fabrication are quite different for each subsystem. In typical systems numerous modeling environments are incorporated to satisfy the requirements of each subsystem. An approach which incorporates several different modeling environments has several drawbacks. First, it is error-prone and inefficient since models must be transformed between each separate environment. Second, non-uniform data structures make the software more difficult to manage. Finally, it is not easily extendible to new system applications which may require a mixture of the attributes of different environments. To address these problems, our manufacturing system is built upon a geometric modeling environment, NOODLES [10], where subsystem models share a common representational and manipulation scheme.

The following examples demonstrate some of the diverse modeling requirements for this CAD-based manufacturing system:

- The user designing a part should be allowed to select the appropriate modeling description paradigm depending upon the immediate need. For example, designs, at times, can best be synthesized using constructive solid geometry, while at others, sweeping lower dimensional elements, such as curves and surfaces, into solid representations produce more satisfactory results.

- The SLA process planner must convert solid models into an ordered set of 2-1/2 D cross-sections (i. e cross sections with an associated depth or thickness) and span these cross-sections with appropriate drawing vectors. This operation inherently involves working simultaneously in several dimensions since one generates planes from solid models, and then vectors, or line segments, from the planes. Also, the analysis of the injection molding process with finite element methods requires the transformation of the solid model into 2-1/2 dimensional meshes.

- The robotic spray planner operates with yet other abstractions. Grids are projected onto the object's shell to produce surface patches which are analyzed for spraying action. In turn, the spraying actions are modeled as curvilinear paths which sweep the relevant portions of the tool geometry into volumes for interference testing. At this level, assessing the interference is not constrained to be intersections between solids, but also intersections between surfaces and surfaces, or surfaces and solids.

- One difficulty in modifying a part's geometry is the challenge of maintaining the part's validity during the modification. This problem appears in all operations that modify a part, such as those that alter a part's draft angles to make it better for injection molding. For illustration, a solid represented by a cube with a pyramid on top is valid. If the geometry is modified by pushing the vertex of the pyramid into the cube, the solid remains valid, until the vertex is pushed through the bottom of the cube. At that time, the solid has been modified into a *non-valid* object. New edges and vertices must be added to the part's representation to account for those created by the intersection of the pyramid and the bottom of the cube. Precisely the same situation may arise when changing the slopes of a part's sides to increase draft angles, or altering features to make the part more manufacturable in other ways.

- Features are the most complex level of abstraction for this system. A feature is defined as any geometric form or entity that is used in reasoning in one or more design or manufacturing activities [2]. The spray planning system, for example, needs to extract convex corner features from the geometric descriptions in order to properly aim the spray to avoid overspray. The injection mold evaluator needs to identify rib features to analyze them for sufficient taper. And, an SLA planner needs to identify overhangs and ledges, for example, for support structure design.

Geometric modeling can be performed at various levels, such as wire-frame, surface, or solid modeling.

The previous examples suggest that all levels are required in the system. Although solid modeling approaches have the richest information, the representation of lower level elements such as lines and surfaces is not explicit. Furthermore, operations provided within solid modeling approaches do not apply when non-solid elements are used. The ideal geometric modeling system should uniformly represent non-homogeneous (i.e. mixed dimensions) elements such as lines, surfaces, and solids. The modeling operations between these non-homogeneous elements should be defined in a manner that is independent of the dimensionality.

NOODLES offers an environment where non-homogeneous elements are uniformly represented. Since NOODLES is based on a boundary representation approach, the topology is necessarily non-manifold in order to represent the non-homogeneous elements consistently. All such elements are conceived as point sets which are open in their respective dimensions. Furthermore, geometric models are represented as a collection of these opens sets which are mutually exclusive and collectively exhaustive. Hence, every geometric model is a thorough and non-overlapping categorization of the modeling space. The non-manifold topological framework keeps track of the adjacencies between these point sets.

The fundamental operation in NOODLES is the merging of different models into one model where the space is recategorized into disjoint and exhaustive point sets with proper inheritance with respect to the original models. When this fundamental operation is executed, all point set manipulations such as interior, closure, and boolean operations can be trivially performed. The implications of this approach include defining volumes by adding surfaces, and realizing boolean operations between elements of any dimensionality. Furthermore, this approach makes full use of the non-regular nature of boolean operations rather than enforcing regularity.

One example which uses the non-regular operations is the planning of the stereolithography process. The first step is to obtain the cross-sections of the object. These sections are obtained from the boolean intersection between the object and a stack of planar faces that are appropriately spaced. As is shown in Figure 4-1, the result of this non-regular operation is a collection of cross-sections. Identification of the interior and skin-fill areas can also be achieved with set operations. The intersection between the projections of contiguous cross-sections identifies the interior area; the differences between these cross-sections produce the skin-fill areas as illustrated in Figure 4-2. Finally, the vectors to be scanned by the laser are obtained by intersecting appropriate grids with the portions of the cross-section. For example, as shown in Figure 4-3, the interior area of a cross-section is is intersected with a cross-hatch grid. The object boundaries for the laser are quickly found from the perimeters of the cross-sections.

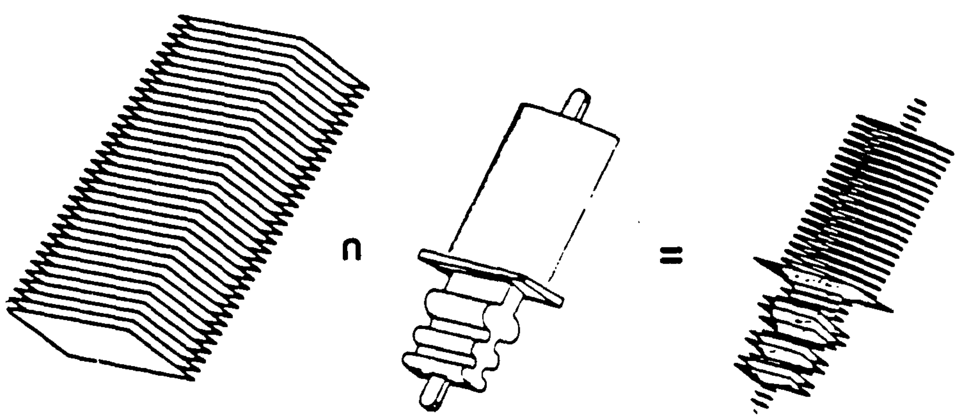


Figure 4-1: Slicing with NOODLES

The result of using NOODLES to generate grids for robotic path planning is depicted in Figure 4-4. The

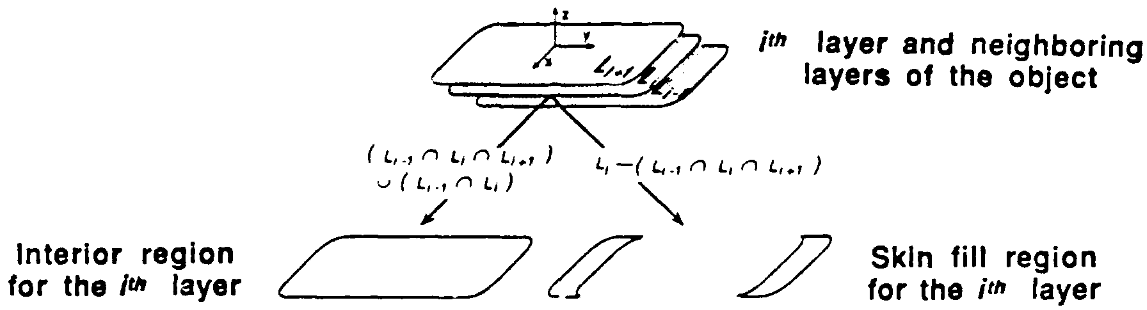


Figure 4-2: Locating skin-fills and interiors with NOODLES

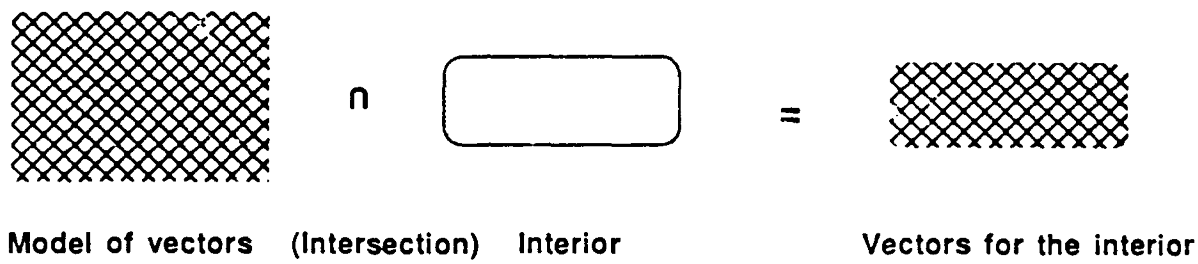


Figure 4-3: Vector generation with NOODLES

grids are defined by the perimeters of the intersection of the surface boundary of the object with two perpendicular sets of stacks of planar faces.

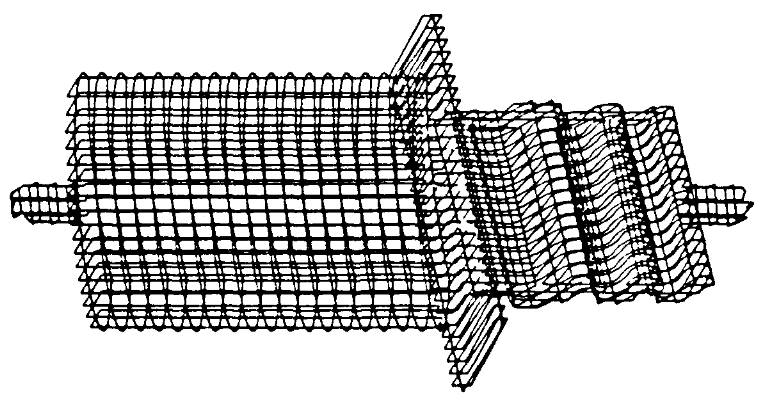


Figure 4-4: Grids generated with NOODLES

A feature extraction algorithm is also being developed which automatically recognizes form features of objects represented in NOODLES [16]. This algorithm, uses a graph grammar to describe and recognize shape features, based on an augmented topology of the modeled objects which contain these features. The NOODLES representation provides the information for construction of the augmented topology graphs. These graphs constitute the search space for the recognition of the subgraphs which correspond to the features. In injection molding, features like ribs and bosses are recognized in this manner [7]. Once a feature is recognized by mapping the descriptive subgraph into the object graph, various regimes in the subgraph are also identified with their counterparts in the surface model. The relevant attributes for a feature can thus be evaluated by referring to the actual representation. For instance, the draft angle attributes of the rib features in an injection molded part is very relevant for assessing ejectability. When a rib is recognized by identifying certain surfaces on the object with the opposing sides of the rib, the draft angle can be computed using the geometric information in the model.

Once attributes of a part are identified, such as the draft angle of a rib, it is possible to use NOODLES operations to modify the geometry and improve the part's manufacturability. One danger, though, is that a model may become in-valid while modifying the geometry. The merge operation within NOODLES is used to re-validate the models. The difficulty occurs at two levels: geometry may be altered that changes the basic topology assumptions of the object (that is, faces may no longer be planar), and secondly, faces, edges, or vertices may be moved into intersection by the geometry alterations. The first problem can happen when only one vertex on a four sided planar face is moved to, say, improve draft angle; the face becomes non-planar. The second problem, self-intersection, can occur at any time when geometry is modified for manufacturability reasons.

The re-validating operation operates in two stages. First, new edges are created to break non-linear faces into several planar faces. Forcing the entire model, for example, to have only triangular facets satisfies the first difficulty. Secondly, the model is *separated* into component topological entities, and then *re-merged* into the single model. During this process, the merge operation automatically creates new nodes and edges to account for intersecting edges or faces. In practice, this operation is expensive, but certain adjacency data in the model can be used to speed the process in future implementations.

5. Robotic Spraying

The need to accurately execute spray paths based on expert knowledge and to consistently repeat operations makes a robotic system essential in the rapid tool manufacturing domain. Arc spraying robots [15, 19] currently provide repeatability in surface coating applications. However, the spray paths are manually generated with a teach pendant for all but the simplest of part geometries. Automated and intelligent decision making capabilities, using design models and expert knowledge for off-line path generation, are absent from these systems.

Automated thermal spraying requires the scheduling of the arc spray parameters and the selection of the robot trajectory. The arc parameters include: arc voltage, wire feed rate, atomizing gas pressure, atomizing gas type, wire diameter, and nozzle geometry. Because the number of parameters is high, an experimental testbed is crucial to systematically study how these parameters individually and as a whole affect shell quality. In the domain of surface coating applications, statistical methods exist to tune the thermal spray process parameters to produce optimal coating quality [21]. Extending the optimization to include the robot trajectory provides added dimensions to the problem which have not been addressed before. This chapter focuses on the trajectory planning issues and motion optimization. Planning in the workspace involves determining the relative path of the spray on the part; feature-based path planning is identified as one approach. Robot trajectory optimization is then presented, and involves transforming the workspace paths into the robot's joint coordinates as well as determining optimal fixturing and part locations.

5.1 Path Planning

Arc parameters directly affect the sprayed shell quality [20]. Of equal importance is the path of the gun. For example, consider the phenomenon of overspray as shown in Figure 5-1. Particle trajectories should align with the surface normals to assure maximal splattering of the molten particles. As the angle of impingement increases, that is as the angle between the particle trajectory and the surface normal increase, the shell quality degrades. After some critical impingement angle, θ_c, the particles bounce-off the surface as wasted overspray or become entrapped in the shell reducing its strength. While θ_c is a function of the spray parameters, θ_c=45 degrees has been used as a rule-of-thumb [6]. The amount of overspray generated is therefore dependent upon the gun orientation relative to the part surface. The following examples illustrate how this information can be accounted for in planning.

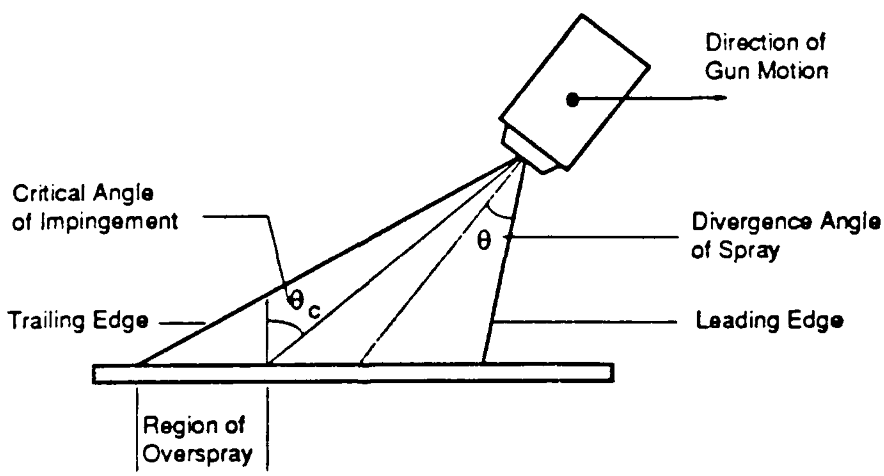


Figure 5-1: Overspray

First consider a simple planning algorithm, where the spray path is defined by a grid on the surface of the workpiece. Generating such a grid was demonstrated in chpater 4. In this algorithm, the spray gun is oriented normal to the surface and follows each line of the grid with a constant standoff distance. We refer to this strategy as the surface-normal tracking strategy. To analyze the overspray performance of this strategy, consider the convex corner of the cross section shown in Figure 5-2A. θ is defined as the spray divergence angle. There is no overspray as long as all of the spray hits a flat surface, the gun axis is perpendicular to the flat surface, and $\theta \leq \theta_c$. However, this strategy produces overspray on both the vertical and horizontal surfaces as the gun negotiates the corner.

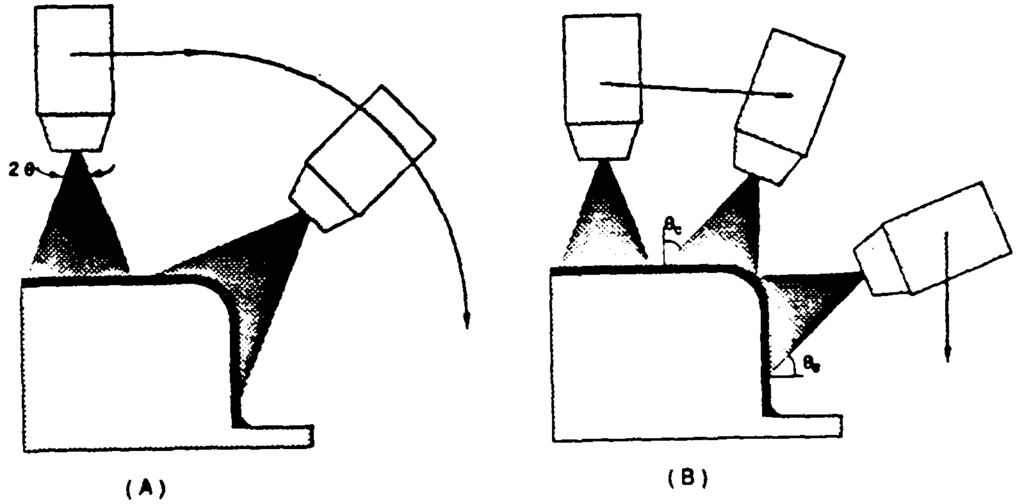


Figure 5-2: Spray paths

An alternative two-step strategy shown in Figure 5-2B eliminates overspray for this particular example. As the gun approaches the corner it is oriented so that the trailing edge of the spray cone makes an incident angle of θ_c. As the leading edge starts traversing the curved surface, its incident angle increases and spraying is stopped when it becomes θ_c. At this time both the leading and the trailing edges make incident angles of θ_c so there is no overspray on any surface. The gun is then reoriented so that the leading edge makes an incident angle of θ_c with the vertical surface, and repositioned so that the trailing edge makes an incident angle of θ_c with the curved surface. Spraying is restarted from this position and proceeds down the vertical surface.

These two strategies demonstrate spray planning for a simplified two dimensional cases. In practice, strategies will have to be synthesized which account for the interaction of the spray cone with three dimensional and more complex shapes, and which address a range of spray performance requirements. However, these examples demonstrate one important result. Although both strategies are based on the geometry of the object, the latter also considers process limitations. Within a framework based on the combination of geometry and process, a superior strategy was developed. The cases where this strategy apply can be identified by recognizing the corner feature where the overspray condition exists. Finding the critical corners can be done by algebraically searching the path for the overspray condition. Alternately, the search algorithm can be changed by explicitly identifying the features. Then feature-based planning can provide two advantages. First, once the features are identified, spray problem areas are quickly found. Secondly, successful strategies, predetermined for each feature, can quickly be incorporated into the plan.

Features of interest to the spray process, such as corners, depressions, and protrusions, are rarely of interest to the designer in initial design stages. Furthermore the interaction of features associated with the primitive shapes used to build up a design produces new unexpected features as well as destroys the original features. Therefore while the known features of some primitive shapes may be retained for specific design applications, feature extraction is required in a robust system. The capability to define and extract three dimensional features is being developed within the NOODLES environment [16] as outlined in chapter 4.

There are particular cases in the sprayed tool process where features may be tagged ahead of time which will simplify planning. For this, NOODLES permits labels and attributes for each topological element. For example, adherence of the first few sprayed layers is improved by spraying rougher areas first. In our process, the inside of the frame (Step 3. Figure 3-3) is roughened, and these surfaces can be labeled as "rough". The planner could then use a strategy which first deposits a few layers around the inside of the frame and then spray from there onto the parting plane surface.

One goal of our research is to identify a useful set of features for spray planning and to develop effective spray strategies for them. The complexity of this spray process and its interactions with part geometry mandates process modeling based on experimentation and empirical observation to achieve this goal.

5.2 Robotic Trajectory Optimization

In our spray system there are 12 robotic degrees-of-freedom (DOF) including: a 6 DOF robot, a 1 DOF servo turntable upon which the workpiece sits, 2 DOFs to specify the placement of the workpiece on the table, 2 DOFs to locate the turntable in the workspace, and 1 DOF to orient the turntable. The robot and turntable are simultaneously moved in a coordinated fashion during spraying, while the remaining DOFs are chosen for a particular part and fixed during spraying.

The spray paths must be mapped into these 12 DOFs. This is a nontrivial problem because the 12 DOFs are redundant; there are no unique solutions. The spray paths are specified by 5 DOFs since rotation about the gun axis does not change a conical spray pattern. We are applying an existing robotic welding path optimizer [13] to find an optimal solution by defining a cost function of the 12 DOFs and minimizing it for the particular spray path. Some examples of optimization include minimizing robot joint sweeps and changes in velocity. The former allows the robot to work in more constrained areas. The latter helps to reduce motion error.

Optimization schemes can be local or global. Local schemes use the current joint positions and the direction to move, while global schemes use the information about the whole path. Local optimizations suffer from the short sighted nature of the approach, but are relatively computationally inexpensive; whereas the reverse is true for global optimization. In fact, the computational expenses of the latter approach makes it a necessarily off-line strategy. Hemmerle's optimizer [13] is a global position-based approach. This algorithm operates with a set of points along the path instead of a function describing the continuous path. The cost function is a function of the robot joint positions at each point. Constraints on robot motion, defined in joint coordinates, such as keeping the joints away from some predetermined limits, can be incorporated in this optimization in a straightforward manner. If the constraint functions are dependent on derivatives of the position, such as velocity and acceleration, a finite difference approximation is used to incorporate them in this algorithm.

Trajectory planning must also address obstacle avoidance, in Cartesian coordinates, due to the the finite dimensions of a spray hood. A hood, which the robot reaches into during spraying, and exhaust system are required to trap and to collect the dust particles of the overspray. An extension to the current trajectory planner will account for the hood spatial constraints within the cost function of the optimization scheme. The approach being considered is to model the robot and the obstacles with simple primitives and to determine the closest distance between the robot and the obstacle at each point. The cost function will incorporate this distance to keep it above a limiting minimum.

6. Discussion

This report presents a framework for a rapid tool manufacturing system based upon the integration of stereolithography and thermal spraying. These processes are particularly well suited for building complex shapes. The basic fabrication processes have been demonstrated experimentally, the system issues have been identified, and our current research directions have been outlined including automated spraying and geometric modeling. A testbed is being built within this framework. The extension of this system to superior prototype tools and production-quality tooling will require research and development into steel-based sprayed tools. The realization of a complete system will also require R&D in several other areas including: improved spray gun designs, more accurate SLA parts, process planning for shaping deposition processes, robust 3D feature extraction, and CAD tools for evaluating design manufacturability.

High-volume production-quality manufacturing and prototype tools used for high impact loading applications, such as stamping, require steel tooling. This requires not only the capability to spray steel shells, but also to develop complimentary backing materials. These materials must have matching coefficients of thermal expansion with steel, and have sufficient ruggedness and strength. This backing requirement may be extremely difficult to achieve for mass production tools requiring tens-of-thousands of loading cycles and high impact resistance. An incremental approach would be to first develop backing materials for *low-batch* production steel tools. Such tools would have several advantages:

1. Die designs prototyped in zinc-based alloys, including those conventionally machined from Kirksite, often do not adequately predict the performance of their machined steel counterparts. Surface frictional and thermal characteristics differ for these materials. The machined steel dies must then be further iterated to achieve acceptable performance. This process is costly and time consuming. Sprayed steel prototype tools would more accurately predict the performance of machined steel tools and would reduce the number of redesign/refabrication iterations.

2. If sprayed steel tools could be made *on-demand* and inexpensively and also be able to withstand thousands of cycles, then multiple tools could be produced as needed for use in production. This gives the advantage of quicker response to market demands.

Our initial experimentation shows that 420 stainless steel, for example, can be deposited onto SLA parts without distorting the plastic. However, the process for steel is less forgiving than for zinc. Therefore robotic spraying seems to be critical to *reliably* and *consistently* spray steel. One significant challenge for steel spraying will be to find a release agent which meets the needs of withstanding the heat of the molten metal, of being strong enough to hold the sprayed metal in the presence of considerable stress, and of releasing after spraying. Release agents, currently proprietary, exist which begin to satisfy these requirements.

Another approach to fabricating production quality tooling is to use electric discharge machining (EDM) to form high-quality steel dies The EDM process can be enhanced for forming complex shapes by first manufacturing the EDM electrodes using the SLA/thermal spray system concept to reduce the costs and time to produce the electrodes. The process would include: build an SLA die pattern of the complement of the desired EDM shape, add a frame and then spray the die pattern with copper, insert electrode conductor wire, and finally backup the copper shell. Multiple electrodes are typically required for roughing and then for fine detail and can quickly be made with spraying.

For "hard to spray shapes" there are a number of possible directions to pursue. While the accurate aiming capability of robotic spraying will be helpful, the ability to spray concave shapes with small aspect ratios (e.g. small deep holes) is still limited by the divergence of particles from the spray gun and and the limitation of spraying along the line of sight. New gun nozzle designs which produce narrower spray patterns would helpful. The trade-off as the spray beam narrows may be in-flight coalesence of the particles deteriorating spray performance. A systematic approach to gun nozzle design remains a fruitful area of research which has yet to be addressed in the literature. Arc gun "inside-diameter" extensions are available which deflect the spray at approximately 90 degrees to the gun axis and are used for spraying inside vessels, cylinders, and convex shapes. However, these adaptors are currently limited to a minimum opening of about two inches. For shapes which will be impossible to spray, metal inserts will be required. In addition to equipment improvements, the design system should account for "hard to spray shapes" by having up-to-date knowledge of the spray capabilities. Such a system should give feedback to the part designer about the manufacturing process ramifications of part geometry prior to the fabrication stage. Our system will build upon ongoing research, at Carnegie Mellon, on design for manufacturing [5].

The current accuracy of SLA parts is on the order of .010 inches while surface texture is dependent on the building orientation. Additional postprocesing, such as carefully sanding and grinding the part, is therefore required for making accurate and smooth mold patterns. Since stereolithography is so new, we expect rapid improvements as the equipment and resins evolve with broadening commercial competition. Even with such improvements, process planning for stereolithography, remains crucial. The consistency of the parts they build is dependent upon developing formalized approaches to assist programmers in finding optimal parameter sets. Basing process planning on classical optimization schemes, by defining cost-functions and using numerical search techniques to find optimal sets, is one possible approach. For example, when the designer is creating an SLA part and deciding upon part orientation, slice thickness', and support structures, trade-offs must generally be made between part build time, surface appearance, part dimensional accuracy, and postprocessing requirements. The goals of minimum build time, excellent part quality, and minimum post processing frequently conflict, so their relative importance to a particular application can be weighted in a performance index as a function of the SLA parameters.

The shaping deposition processes are highly dependent upon geometry and effective process planning should also incorporate geometric feature information. This approach has already been demonstrated for robot path planning. Another example includes the use of features to help select candidate orientations for SLA building to narrow the search space in a numerical search scheme. For example, the system might identify cylindrical shapes and include candidate orientations, in the optimization set, which align the cylindrical axis' in z-direction of the SLA vat to achieve smooth surface appearance for these shapes. Further, CAD-based support structure design could incorporate feature-based planning by associating preselected support structures with design features such as ledges and overhangs. The development of robust feature extraction algorithms for these planning systems remains a challenge. The approach by Pinilla [16] is one possible solution.

In conclusion, we feel that a testbed based on stereolithography and thermal spraying integrated in a unifying CAD environment will help prove the promise of timely and cost-effective tool manufacture.

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